

METHOD AND SYSTEM FOR TRANSMITTING INFORMATION  
IN AN OPTICAL COMMUNICATION SYSTEM USING  
DISTRIBUTED AMPLIFICATION

RELATED PATENT APPLICATIONS

*INSAY*

This application is related to U.S. Patent Application Serial No. \_\_\_\_\_ entitled "Receiver and Method for a Multichannel Optical Communication System," U.S. Patent Application Serial No. \_\_\_\_\_ entitled "Method and System for Demultiplexing Non-Intensity Modulated Wavelength Division Multiplexed (WDM) Signals," and U.S. Patent Application Serial No. \_\_\_\_\_ entitled "Method and System for Tuning an Optical Signal Based on Transmission Conditions," and U.S. Patent Application Serial No. \_\_\_\_\_ entitled "Method and System for Communicating a Clock Signal Over an Optical Link, all filed on \_\_\_\_\_, 2001.

TECHNICAL FIELD OF THE INVENTION

The present invention relates generally to optical communication systems, and more particularly to a method and system for transmitting information in an optical communication system using distributed amplification.

BACKGROUND OF THE INVENTION

Telecommunications systems, cable television systems and data communication networks use optical networks to rapidly convey large amounts of information between remote points. In an optical network, information is conveyed in the form of optical signals through optical fibers. Optical fibers are thin strands of glass capable of transmitting the signals over long distances with very low loss.

Optical networks often employ wavelength division multiplexing (WDM) to increase transmission capacity. In a WDM network, a number of optical channels are carried in each fiber at disparate wavelengths. Network capacity is increased as a multiple of the number of wavelengths, or channels, in each fiber.

The maximum distance that a signal can be transmitted in a WDM or other optical network without amplification is limited by absorption, scattering and other loss associated with the optical fiber. To transmit signals over long distances, optical networks typically include a number of discrete amplifiers spaced along each fiber route. The discrete amplifiers boost received signals to compensate for transmission losses in the fiber.

Signals may also be boosted in the fiber using Raman effect amplification. In the Raman effect, optical signals traveling in the fiber are amplified by the presence of a lower wavelength pump light traveling in the same fiber. The pump light may travel forward with the signal or backwards in reverse of the signal. Because forward pumping amplification causes cross talk between channels in WDM systems due to cross gain modulation (XGM), reverse pumping amplification is

typically used in connection with WDM and other  
multichannel systems. This limits the use of Raman  
effect amplification in multichannel systems to  
unidirectional transmission fibers and prevents bi-  
5 directional distributed amplification.

SUMMARY OF THE INVENTION

The present invention provides an improved method and system for transmitting information in an optical communication system using distributed amplification. In a particular embodiment, phase, frequency or other non-intensity modulated information signals are used to transmit data across an optical link which allows for forward, or co-pumping, and backward, or counter-pumping, distributed Raman amplification (DRA) while still providing a superior signal-to-noise ratio.

In accordance with one embodiment of the present invention, a method and system for transmitting information in an optical communication system includes modulating a non-intensity characteristic of an optical carrier signal with a data signal to generate an optical information signal. The optical information signal is transmitted over an optical link. The optical information signal is amplified over a length of the optical link with a co-launched amplification signal traveling in the optical link in a same direction as the optical information signal.

More specifically, in accordance with a particular embodiment of the present invention, the optical information signal is amplified with the co-launched amplification signal by DRA. In this and other embodiments, the optical information signal may be multiplexed with other optical information signals to generate a wavelength division multiplexed (WDM) signal for transmission over the optical link. The non-intensity modulation characteristic may comprise the phase and/or frequency of the carrier signal.

In accordance with another aspect of the present invention, the optical information signal may be

remodulated with a transmission clock frequency using an intensity modulator to generate a multimodulated signal. The multimodulated signal is transmitted over the optical link and amplified over the length of the optical link with the co-launched amplification signal.

Technical advantages of the present invention include providing an improved method and system for transmitting information in an optical communication system using distributed amplification. In a particular embodiment, phase or frequency modulation is used to transmit data over an optical fiber to allow bi-directional DRA without cross talk between channels due to cross-gain modulation (XGM). As a result, signals may be transmitted over longer distances with high signal-to-noise ratios and DRA may be used in connection with long-haul optical transmission systems.

Another technical advantage of one or more embodiments of the present invention includes providing a bi-directional multichannel optical communication system using distributed amplification. In particular, data is transported using non-intensity modulation to allow data transmission in the forward and reverse directions of DRA pump lasers. Accordingly, amplification of bi-directional communication systems are improved and distances over which data may be communicated bi-directionally is increased.

Still another technical advantage of one or more embodiments of the present invention include providing an optical transmission system with improved power tolerance. In particular, data is modulated using phase or frequency shift keying to eliminate XGM with the resulting signal being remodulated with the transmission clock using intensity modulation. As a result, non-

linear and chromatic effects creating signal recovery problems at phase edges are minimized while still allowing for forward and/or reverse DRA and high signal-to-noise ratios.

- 5 Other technical advantages of the present invention will be readily apparent to one skilled in the art from the following figures, description and claims.

11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60  
61  
62  
63  
64  
65  
66  
67  
68  
69  
70  
71  
72  
73  
74  
75  
76  
77  
78  
79  
80  
81  
82  
83  
84  
85  
86  
87  
88  
89  
90  
91  
92  
93  
94  
95  
96  
97  
98  
99  
100  
101  
102  
103  
104  
105  
106  
107  
108  
109  
110  
111  
112  
113  
114  
115  
116  
117  
118  
119  
120  
121  
122  
123  
124  
125  
126  
127  
128  
129  
130  
131  
132  
133  
134  
135  
136  
137  
138  
139  
140  
141  
142  
143  
144  
145  
146  
147  
148  
149  
150  
151  
152  
153  
154  
155  
156  
157  
158  
159  
160  
161  
162  
163  
164  
165  
166  
167  
168  
169  
170  
171  
172  
173  
174  
175  
176  
177  
178  
179  
180  
181  
182  
183  
184  
185  
186  
187  
188  
189  
190  
191  
192  
193  
194  
195  
196  
197  
198  
199  
200  
201  
202  
203  
204  
205  
206  
207  
208  
209  
210  
211  
212  
213  
214  
215  
216  
217  
218  
219  
220  
221  
222  
223  
224  
225  
226  
227  
228  
229  
230  
231  
232  
233  
234  
235  
236  
237  
238  
239  
240  
241  
242  
243  
244  
245  
246  
247  
248  
249  
250  
251  
252  
253  
254  
255  
256  
257  
258  
259  
260  
261  
262  
263  
264  
265  
266  
267  
268  
269  
270  
271  
272  
273  
274  
275  
276  
277  
278  
279  
280  
281  
282  
283  
284  
285  
286  
287  
288  
289  
290  
291  
292  
293  
294  
295  
296  
297  
298  
299  
300  
301  
302  
303  
304  
305  
306  
307  
308  
309  
310  
311  
312  
313  
314  
315  
316  
317  
318  
319  
320  
321  
322  
323  
324  
325  
326  
327  
328  
329  
330  
331  
332  
333  
334  
335  
336  
337  
338  
339  
340  
341  
342  
343  
344  
345  
346  
347  
348  
349  
350  
351  
352  
353  
354  
355  
356  
357  
358  
359  
360  
361  
362  
363  
364  
365  
366  
367  
368  
369  
370  
371  
372  
373  
374  
375  
376  
377  
378  
379  
380  
381  
382  
383  
384  
385  
386  
387  
388  
389  
390  
391  
392  
393  
394  
395  
396  
397  
398  
399  
400  
401  
402  
403  
404  
405  
406  
407  
408  
409  
410  
411  
412  
413  
414  
415  
416  
417  
418  
419  
420  
421  
422  
423  
424  
425  
426  
427  
428  
429  
430  
431  
432  
433  
434  
435  
436  
437  
438  
439  
440  
441  
442  
443  
444  
445  
446  
447  
448  
449  
450  
451  
452  
453  
454  
455  
456  
457  
458  
459  
460  
461  
462  
463  
464  
465  
466  
467  
468  
469  
470  
471  
472  
473  
474  
475  
476  
477  
478  
479  
480  
481  
482  
483  
484  
485  
486  
487  
488  
489  
490  
491  
492  
493  
494  
495  
496  
497  
498  
499  
500  
501  
502  
503  
504  
505  
506  
507  
508  
509  
510  
511  
512  
513  
514  
515  
516  
517  
518  
519  
520  
521  
522  
523  
524  
525  
526  
527  
528  
529  
530  
531  
532  
533  
534  
535  
536  
537  
538  
539  
540  
541  
542  
543  
544  
545  
546  
547  
548  
549  
550  
551  
552  
553  
554  
555  
556  
557  
558  
559  
560  
561  
562  
563  
564  
565  
566  
567  
568  
569  
570  
571  
572  
573  
574  
575  
576  
577  
578  
579  
580  
581  
582  
583  
584  
585  
586  
587  
588  
589  
590  
591  
592  
593  
594  
595  
596  
597  
598  
599  
600  
601  
602  
603  
604  
605  
606  
607  
608  
609  
610  
611  
612  
613  
614  
615  
616  
617  
618  
619  
620  
621  
622  
623  
624  
625  
626  
627  
628  
629  
630  
631  
632  
633  
634  
635  
636  
637  
638  
639  
640  
641  
642  
643  
644  
645  
646  
647  
648  
649  
650  
651  
652  
653  
654  
655  
656  
657  
658  
659  
660  
661  
662  
663  
664  
665  
666  
667  
668  
669  
670  
671  
672  
673  
674  
675  
676  
677  
678  
679  
680  
681  
682  
683  
684  
685  
686  
687  
688  
689  
690  
691  
692  
693  
694  
695  
696  
697  
698  
699  
700  
701  
702  
703  
704  
705  
706  
707  
708  
709  
710  
711  
712  
713  
714  
715  
716  
717  
718  
719  
720  
721  
722  
723  
724  
725  
726  
727  
728  
729  
730  
731  
732  
733  
734  
735  
736  
737  
738  
739  
740  
741  
742  
743  
744  
745  
746  
747  
748  
749  
750  
751  
752  
753  
754  
755  
756  
757  
758  
759  
760  
761  
762  
763  
764  
765  
766  
767  
768  
769  
770  
771  
772  
773  
774  
775  
776  
777  
778  
779  
780  
781  
782  
783  
784  
785  
786  
787  
788  
789  
790  
791  
792  
793  
794  
795  
796  
797  
798  
799  
800  
801  
802  
803  
804  
805  
806  
807  
808  
809  
810  
811  
812  
813  
814  
815  
816  
817  
818  
819  
820  
821  
822  
823  
824  
825  
826  
827  
828  
829  
830  
831  
832  
833  
834  
835  
836  
837  
838  
839  
840  
841  
842  
843  
844  
845  
846  
847  
848  
849  
850  
851  
852  
853  
854  
855  
856  
857  
858  
859  
860  
861  
862  
863  
864  
865  
866  
867  
868  
869  
870  
871  
872  
873  
874  
875  
876  
877  
878  
879  
880  
881  
882  
883  
884  
885  
886  
887  
888  
889  
890  
891  
892  
893  
894  
895  
896  
897  
898  
899  
900  
901  
902  
903  
904  
905  
906  
907  
908  
909  
910  
911  
912  
913  
914  
915  
916  
917  
918  
919  
920  
921  
922  
923  
924  
925  
926  
927  
928  
929  
930  
931  
932  
933  
934  
935  
936  
937  
938  
939  
940  
941  
942  
943  
944  
945  
946  
947  
948  
949  
950  
951  
952  
953  
954  
955  
956  
957  
958  
959  
960  
961  
962  
963  
964  
965  
966  
967  
968  
969  
970  
971  
972  
973  
974  
975  
976  
977  
978  
979  
980  
981  
982  
983  
984  
985  
986  
987  
988  
989  
990  
991  
992  
993  
994  
995  
996  
997  
998  
999  
1000  
1001  
1002  
1003  
1004  
1005  
1006  
1007  
1008  
1009  
1010  
1011  
1012  
1013  
1014  
1015  
1016  
1017  
1018  
1019  
1020  
1021  
1022  
1023  
1024  
1025  
1026  
1027  
1028  
1029  
1030  
1031  
1032  
1033  
1034  
1035  
1036  
1037  
1038  
1039  
1040  
1041  
1042  
1043  
1044  
1045  
1046  
1047  
1048  
1049  
1050  
1051  
1052  
1053  
1054  
1055  
1056  
1057  
1058  
1059  
1060  
1061  
1062  
1063  
1064  
1065  
1066  
1067  
1068  
1069  
1070  
1071  
1072  
1073  
1074  
1075  
1076  
1077  
1078  
1079  
1080  
1081  
1082  
1083  
1084  
1085  
1086  
1087  
1088  
1089  
1090  
1091  
1092  
1093  
1094  
1095  
1096  
1097  
1098  
1099  
1100  
1101  
1102  
1103  
1104  
1105  
1106  
1107  
1108  
1109  
1110  
1111  
1112  
1113  
1114  
1115  
1116  
1117  
1118  
1119  
1120  
1121  
1122  
1123  
1124  
1125  
1126  
1127  
1128  
1129  
1130  
1131  
1132  
1133  
1134  
1135  
1136  
1137  
1138  
1139  
1140  
1141  
1142  
1143  
1144  
1145  
1146  
1147  
1148  
1149  
1150  
1151  
1152  
1153  
1154  
1155  
1156  
1157  
1158  
1159  
1160  
1161  
1162  
1163  
1164  
1165  
1166  
1167  
1168  
1169  
1170  
1171  
1172  
1173  
1174  
1175  
1176  
1177  
1178  
1179  
1180  
1181  
1182  
1183  
1184  
1185  
1186  
1187  
1188  
1189  
1190  
1191  
1192  
1193  
1194  
1195  
1196  
1197  
1198  
1199  
1200  
1201  
1202  
1203  
1204  
1205  
1206  
1207  
1208  
1209  
1210  
1211  
1212  
1213  
1214  
1215  
1216  
1217  
1218  
1219  
1220  
1221  
1222  
1223  
1224  
1225  
1226  
1227  
1228  
1229  
1230  
1231  
1232  
1233  
1234  
1235  
1236  
1237  
1238  
1239  
1240  
1241  
1242  
1243  
1244  
1245  
1246  
1247  
1248  
1249  
1250  
1251  
1252  
1253  
1254  
1255  
1256  
1257  
1258  
1259  
1260  
1261  
1262  
1263  
1264  
1265  
1266  
1267  
1268  
1269  
1270  
1271  
1272  
1273  
1274  
1275  
1276  
1277  
1278  
1279  
1280  
1281  
1282  
1283  
1284  
1285  
1286  
1287  
1288  
1289  
1290  
1291  
1292  
1293  
1294  
1295  
1296  
1297  
1298  
1299  
1300  
1301  
1302  
1303  
1304  
1305  
1306  
1307  
1308  
1309  
1310  
1311  
1312  
1313  
1314  
1315  
1316  
1317  
1318  
1319  
1320  
1321  
1322  
1323  
1324  
1325  
1326  
1327  
1328  
1329  
1330  
1331  
1332  
1333  
1334  
1335  
1336  
1337  
1338  
1339  
1340  
1341  
1342  
1343  
1344  
1345  
1346  
1347  
1348  
1349  
1350  
1351  
1352  
1353  
1354  
1355  
1356  
1357  
1358  
1359  
1360  
1361  
1362  
1363  
1364  
1365  
1366  
1367  
1368  
1369  
1370  
1371  
1372  
1373  
1374  
1375  
1376  
1377  
1378  
1379  
1380  
1381  
1382  
1383  
1384  
1385  
1386  
1387  
1388  
1389  
1390  
1391  
1392  
1393  
1394  
1395  
1396  
1397  
1398  
1399  
1400  
1401  
1402  
1403  
1404  
1405  
1406  
1407  
1408  
1409  
1410  
1411  
1412  
1413  
1414  
1415  
1416  
1417  
1418  
1419  
1420  
1421  
1422  
1423  
1424  
1425  
1426  
1427  
1428  
1429  
1430  
1431  
1432  
1433  
1434  
1435  
1436  
1437  
1438  
1439  
1440  
1441  
1442  
1443  
1444  
1445  
1446  
1447  
1448  
1449  
1450  
1451  
1452  
1453  
1454  
1455  
1456  
1457  
1458  
1459  
1460  
1461  
1462  
1463  
1464  
1465  
1466  
1467  
1468  
1469  
1470  
1471  
1472  
1473  
1474  
1475  
1476  
1477  
1478  
1479  
1480  
1481  
1482  
1483  
1484  
1485  
1486  
1487  
1488  
1489  
1490  
1491  
1492  
1493  
1494  
1495  
1496  
1497  
1498  
1499  
1500  
1501  
1502  
1503  
1504  
1505  
1506  
1507  
1508  
1509  
1510  
1511  
1512  
1513  
1514  
1515  
1516  
1517  
1518  
1519  
1520  
1521  
1522  
1523  
1524  
1525  
1526  
1527  
1528  
1529  
1530  
1531  
1532  
1533  
1534  
1535  
1536  
1537  
1538  
1539  
1540  
1541  
1542  
1543  
1544  
1545  
1546  
1547  
1548  
1549  
1550  
1551  
1552  
1553  
1554  
1555  
1556  
1557  
1558  
1559  
1560  
1561  
1562  
1563  
1564  
1565  
1566  
1567  
1568  
1569  
1570  
1571  
1572  
1573  
1574  
1575  
1576  
1577  
1578  
1579  
1580  
1581  
1582  
1583  
1584  
1585  
1586  
1587  
1588  
1589  
1590  
1591  
1592  
1593  
1594  
1595  
1596  
1597  
1598  
1599  
1600  
1601  
1602  
1603  
1604  
1605  
1606  
1607  
1608  
1609  
1610  
1611  
1612  
1613  
1614  
1615  
1616  
1617  
1618  
1619  
1620  
1621  
1622  
1623  
1624  
1625  
1626  
1627  
1628  
1629  
1630  
1631  
1632  
1633  
1634  
1635  
1636  
1637  
1638  
1639  
1640  
1641  
1642  
1643  
1644  
1645  
1646  
1647  
1648  
1649  
1650  
1651  
1652  
1653  
1654  
1655  
1656  
1657  
1658  
1659  
1660  
1661  
1662  
1663  
1664  
1665  
1666  
1667  
1668  
1669  
1670  
1671  
1672  
1673  
1674  
1675  
1676  
1677  
1678  
1679  
1680  
1681  
1682  
1683  
1684  
1685  
1686  
1687  
1688  
1689  
1690  
1691  
1692  
1693  
1694  
1695  
1696  
1697  
1698  
1699  
1700  
1701  
1702  
1703  
1704  
1705  
1706  
1707  
1708  
1709  
1710  
1711  
1712  
1713  
1714  
1715  
1716  
1717  
1718  
1719  
1720  
1721  
1722  
1723  
1724  
1725  
1726  
1727  
1728  
1729  
1730  
1731  
1732  
1733  
1734  
1735  
1736  
1737  
1738  
1739  
1740  
1741  
1742  
1743  
1744  
1745  
1746  
1747  
1748  
1749  
1750  
1751  
1752  
1753  
1754  
1755  
1756  
1757  
1758  
1759  
1760  
1761  
1762  
1763  
1764  
1765  
1766  
1767  
1768  
1769  
1770  
1771  
1772  
1773  
1774  
1775  
1776  
1777  
1778  
1779  
1780  
1781  
1782  
1783  
1784  
1785  
1786  
1787  
1788  
1789  
1790  
1791  
1792  
1793  
1794  
1795  
1796  
1797  
1798  
1799  
1800  
1801  
1802  
1803  
1804  
1805  
1806  
1807  
1808  
1809  
1810  
1811  
1812  
1813  
1814  
1815  
1816  
1817  
1818  
1819  
1820  
1821  
1822  
1823  
1824  
1825  
1826  
1827  
1828  
1829  
1830  
1831  
1832  
1833  
1834  
1835  
1836  
1837  
1838  
1839  
1840  
1841  
1842  
1843  
1844  
1845  
1846  
1847  
1848  
1849  
1850  
1851  
1852  
1853  
1854  
1855  
1856  
1857  
1858  
1859  
1860  
1861  
1862  
1863  
1864  
1865  
1866  
1867  
1868  
1869  
1870  
1871  
1872  
1873  
1874  
1875  
1876  
1877  
1878  
1879  
1880  
1881  
1882  
1883  
1884  
1885  
1886  
1887  
1888  
1889  
1890  
1891  
1892  
1893  
1894  
1895  
1896  
1897  
1898  
1899  
1900  
1901  
1902  
1903  
1904  
1905  
1906  
1907  
1908  
1909  
1910  
1911  
1912  
1913  
1914  
1915  
1916  
1917  
1918  
1919  
1920  
1921  
1922  
1923  
1924  
1925  
1926  
1927  
1928  
1929  
1930  
1931  
1932  
1933  
1934  
1935  
1936  
1937  
1938  
1939  
1940  
1941  
1942  
1943  
1944  
1945  
1946  
1947  
1948  
1949  
1950  
1951  
1952  
1953  
1954  
1955  
1956  
1957  
1958  
1959  
1960  
1961  
1962  
1963  
1964  
1965  
1966  
1967  
1968  
1969  
1970  
1971  
1972  
1973  
1974  
1975  
1976  
1977  
1978  
1979  
1980  
1981  
1982  
1983  
1984  
1985  
1986  
1987  
1988  
1989  
1990  
1991  
1992  
1993  
1994  
1995  
1996  
1997  
1998  
1999  
2000  
2001  
2002  
2003  
2004  
2005  
2006  
2007  
2008  
2009  
2010  
2011  
2012  
2013  
2014  
2015  
2016  
2017  
2018  
2019  
2020  
2021  
2022  
2023  
2024  
2025  
2026  
2027  
2028  
2029  
2030  
2031  
2032  
2033  
2034  
2035  
2036  
2037  
2038  
2039  
2040  
2041  
2042  
2043  
2044  
2045  
2046  
2047  
2048  
2049  
2050  
2051  
2052  
2053  
2054  
2055  
2056  
2057  
2058  
2059  
2060  
2061  
2062  
2063  
2064  
2065  
2066  
2067  
2068  
2069  
2070  
2071  
2072  
2073  
2074  
2075  
2076  
2077  
2078  
2079  
2080  
2081  
2082  
2083  
2084  
2085  
2086  
2087  
2088  
2089  
2090  
2091  
2092  
2093  
2094  
2095  
2096  
2097  
2098  
2099  
2100  
2101  
2102  
2103  
2104  
2105  
2106  
2107  
2108  
2109  
2110  
2111  
2112  
2113  
2114  
2115  
2116  
2117  
2118  
2119  
2120  
2121  
2122  
2123  
2124  
2125  
2126  
2127  
2128  
2129  
2130  
2131  
2132  
2133  
2134  
2135  
2136  
2137  
2138  
2139  
2140  
2141  
2142  
2143  
2144  
2145  
2146  
2147  
2148  
2149  
2150  
2151  
2152  
2153  
2154  
2155  
2156  
2157  
2158  
2159  
2160  
2161  
2162  
2163  
2164  
2165  
2166  
2167  
2168  
2169  
2170  
2171  
2172  
2173  
2174  
2175  
2176  
2177  
2178  
2179  
2180  
2181  
2182  
2183  
2184  
2185  
2186  
2187  
2188  
2189  
2190  
2191  
2192  
2193  
2194  
2195  
2196  
2197  
2198  
2199  
2200  
2201  
2202  
2203  
2204  
2205  
2206  
2207  
2208

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the present invention and its advantages, reference is now made to the following description taken in conjunction with the accompanying drawings, wherein like numerals represent  
5 like parts, in which:

FIGURE 1 is a block diagram illustrating an optical communication system using distributed amplification in accordance with one embodiment of the present invention;

10 FIGURE 2 is a block diagram illustrating the optical sender of FIGURE 1 in accordance with one embodiment of the present invention;

FIGURES 3A-C are diagrams illustrating non-intensity modulated signals for transmission in the optical communication system of FIGURE 1 in accordance with  
15 several embodiments of the present invention;

FIGURE 4 is a block diagram illustrating the optical sender of FIGURE 1 in accordance with another embodiment of the present invention;

20 FIGURE 5 is a diagram illustrating the optical waveform generated by the optical sender of FIGURE 4 in accordance with one embodiment of the present invention;

FIGURE 6 is a block diagram illustrating the optical receiver of FIGURE 1 in accordance with one embodiment of  
25 the present invention;

FIGURE 7 is a diagram illustrating the frequency response of the asymmetric Mach-Zender interferometer of FIGURE 6 in accordance with one embodiment of the present invention;

30 FIGURES 8A-C are block diagrams illustrating the demultiplexer of FIGURE 1 in accordance with several embodiments of the present invention;

FIGURE 9 is a flow diagram illustrating a method for communicating data over an optical communication system using distributed amplification in accordance with one embodiment of the present invention;

5       FIGURE 10 is a block diagram illustrating a bi-directional optical communication system using distributed amplification in accordance with one embodiment of the present invention;

10       FIGURE 11 is a block diagram illustrating the optical sender and receiver of FIGURE 1 in accordance with another embodiment of the present invention;

15       FIGURE 12 is a block diagram illustrating the modulator of FIGURE 11 in accordance with one embodiment of the present invention;

20       FIGURE 13 is a flow diagram illustrating a method for tuning the modulation depth of an optical signal based on receiver side information in accordance with one embodiment of the present invention;

25       FIGURE 14 is a block diagram illustrating an optical communication system distributing a clock signal in an information channel in accordance with one embodiment of the present invention; and

30       FIGURE 15 is a block diagram illustrating an optical receiver for extracting a clock signal from a multimodulated signal in accordance with one embodiment of the present invention.



DETAILED DESCRIPTION OF THE INVENTION

FIGURE 1 illustrates an optical communication system 10 in accordance with one embodiment of the present invention. In this embodiment, the optical communication system 10 is a wavelength division multiplexed (WDM) system in which a number of optical channels are carried over a common path at disparate wavelengths. It will be understood that the optical communication system 10 may comprise other suitable single channel, multichannel or bi-directional transmission systems.

Referring to FIGURE 1, the WDM system 10 includes a WDM transmitter 12 at a source end point and a WDM receiver 14 at a destination end point coupled together by an optical link 16. The WDM transmitter 12 transmits data in a plurality of optical signals, or channels, over the optical link 16 to the remotely located WDM receiver 14. Spacing between the channels is selected to avoid or minimize cross talk between adjacent channels. In one embodiment, as described in more detail below, minimum channel spacing (df) comprises a multiple of the transmission symbol and/or bit rate (B) within 0.4 to 0.6 of an integer (N). Expressed mathematically:  $(N+0.4)B < df < (N+0.6)B$ . This suppresses neighboring channel cross talk. It will be understood that channel spacing may be suitably varied without departing from the scope of the present invention.

The WDM transmitter 12 includes a plurality of optical senders 20 and a WDM multiplexer 22. Each optical sender 20 generates an optical information signal 24 on one of a set of distinct wavelengths  $\lambda_1, \lambda_2 \dots \lambda_n$  at the channel spacing. The optical information signals 24 comprise optical signals with at least one characteristic modulated to encode audio, video, textual,

real-time, non-real-time or other suitable data. The optical information signals 24 are multiplexed into a single WDM signal 26 by the WDM multiplexer 22 for transmission on the optical link 16. It will be  
5 understood that the optical information signals 24 may be otherwise suitably combined into the WDM signal 26. The WDM signal is transmitted in the synchronous optical network (SONET) or other suitable format.

The WDM receiver 14 receives, separates and decodes  
10 the optical information signals 24 to recover the included data. In one embodiment, the WDM receiver 14 includes a WDM demultiplexer 30 and a plurality of optical receivers 32. The WDM demultiplexer 30 demultiplexes the optical information signals 24 from the  
15 single WDM signal 26 and sends each optical information signal 24 to a corresponding optical receiver 32. Each optical receiver 32 optically or electrically recovers the encoded data from the corresponding signal 24. As used herein, the term each means every one of at least a  
20 subset of the identified items.

The optical link 16 comprises optical fiber or other suitable medium in which optical signals may be transmitted with low loss. Interposed along the optical link 16 are one or more optical amplifiers 40. The  
25 optical amplifiers 40 increase the strength, or boost, one or more of the optical information signals 24, and thus the WDM signal 26, without the need for optical-to-electrical conversion.

In one embodiment, the optical amplifiers 40  
30 comprise discrete amplifiers 42 and distributed amplifiers 44. The discrete amplifiers 42 comprise rare earth doped fiber amplifiers, such as erbium doped fiber amplifiers (EDFAs), and other suitable amplifiers

operable to amplify the WDM signal 26 at a point in the optical link 16.

The distributed amplifiers 44 amplify the WDM signal 26 along an extended length of the optical link 16. In one embodiment, the distributed amplifiers 44 comprise bi-directional distributed Raman amplifiers (DRA). Each bi-directional DRA 44 includes a forward, or co-pumping source laser 50 coupled to the optical link 16 at a beginning of the amplifier 44 and a backward, or counter-pumping source laser 52 coupled to the optical link 16 at an end of the amplifier 44. It will be understood that the co-pumping and counter-pumping source lasers 50 and 52 may amplify disparate or only partially overlapping lengths of the optical link 16.

The Raman pump sources 50 and 52 comprise semiconductor or other suitable lasers capable of generating a pump light, or amplification signal, capable of amplifying the WDM signal 26 including one, more or all of the included optical information signals 24. The pump sources 50 and 52 may be depolarized, polarization scrambled or polarization multiplexed to minimize polarization sensitivity of Raman gain.

The amplification signal from the co-pumping laser 52 is launched in the direction of travel of the WDM signal 26 and thus co-propagated with the WDM signal 26 at substantially the same speed and/or a slight or other suitable velocity mismatch. The amplification signal from the counter-pumping laser 52 is launched in a direction of travel opposite that of the WDM signal 26 and thus is counter-propagated with respect to the WDM signal 26. The amplification signals may travel in opposite directions simultaneously at the same or other suitable speed.

The amplification signals comprise one or more high power lights or waves at a lower wavelength than the signal or signals to be amplified. As the amplification signal travels in the optical link 16, it scatters off atoms in the link 16, loses some energy to the atoms and continues with the same wavelength as the amplified signal or signals. In this way, the amplified signal acquires energy over many miles or kilometers in that it is represented by more photons. For the WDM signal 26, the co-pumping and counter-pumping lasers 50 and 52 may each comprise several different pump wavelengths that are used together to amplify each of the wavelength distincts optical information signals 24.

In one embodiment, as described in more detail below, a non-intensity characteristic of a carrier signal is modulated with the data signal at each optical sender 20. The non-intensity characteristic comprises phase, frequency or other suitable characteristic with no or limited susceptibility to cross talk due to cross-gain modulation (XGM) from a forward pumping distributed amplifier or a bi-directional pumping distributed amplifier. The non-intensity modulated optical information signal may be further and/or remodulated with a clock or other non-data signal using an intensity modulator. Thus, the non-intensity modulated optical information signal may comprise intensity modulation of a non-data signal.

In a particular embodiment, as described in more detail below, the WDM signal 26 comprises phase or frequency modulated optical information signals 24 which are amplified using the bi-directional DRAs 44 with no cross talk between the channels 24 due to XGM. In this embodiment, the bi-directional DRAs 44 provide

amplification at a superior optical signal-to-noise ratio and thus enable longer transmission distances and improved transmission performance.

FIGURE 2 illustrates details of the optical sender  
5 20 in accordance with one embodiment of the present invention. In this embodiment, the optical sender 20 comprises a laser 70, a modulator 72 and a data signal 74. The laser 70 generates a carrier signal at a prescribed frequency with good wavelength control.  
10 Typically, the wavelengths emitted by the laser 70 are selected to be within the 1500 nanometer (nm) range, the range at which the minimum signal attenuation occurs for silica-based optical fibers. More particularly, the wavelengths are generally selected to be in the range  
15 from 1310 to 1650 nm but may be suitably varied.

The modulator 72 modulates the carrier signal with the data signal 74 to generate the optical information signal 24. The modulator 72 may employ amplitude modulation, frequency modulation, phase modulation,  
20 intensity modulation, amplitude-shift keying, frequency-shift keying, phase-shift keying and other suitable techniques for encoding the data signal 74 onto the carrier signal. In addition, it will be understood that different modulators 72 may employ more than one  
25 modulation system in combination.

*INS 127* In accordance with one embodiment, modulator 74 modulates the phase, frequency or other suitable non-intensity characteristic of the carrier signal with the data signal 74. As previously described, this generates  
30 a non-intensity optical information signal 24 with poor susceptibility to cross talk due to XGM in long-haul and other transmission systems using bi-directional DRA or other distributed amplification. Details of the carrier

wave, frequency modulation of the carrier wave and phase modulation of the carrier wave are illustrated in FIGURES 3A-C.

Referring to FIGURE 3A, the carrier signal 76 is a completely periodic signal at the specified wavelength. The carrier signal 76 has at least one characteristic that may be varied by modulation and is capable of carrying information via modulation.

Referring to FIGURE 3B, the frequency of the carrier signal 76 is modulated with a data signal 74 to generate a frequency modulated optical information signal 78. In frequency modulation, the frequency of the carrier signal 76 is shifted as a function of the data signal 74. Frequency shift keying may be used in which the frequency of the carrier signal shifts between discrete states.

Referring to FIGURE 3C, the phase of the carrier signal 76 is modulated with a data signal 80 to generate a phase modulated optical information signal 82. In phase modulation, the phase of the carrier signal 76 is shifted as a function of the data signal 80. Phase shift keying may be used in which the phase of the carrier signal shifts between discrete states.

FIGURE 4 illustrates an optical sender 80 in accordance with another embodiment of the present invention. In this embodiment, data is phase or frequency modulated onto the carrier signal and then remodulated with intensity modulation synchronized with the signal clock to provide superior power tolerance in the transmission system.

Referring to FIGURE 4, the optical sender 80 includes a laser 82, a non-intensity modulator 84 and data signal 86. The non-intensity modulator 84 modulates the phase or frequency of the carrier signal from the

laser 82 with the data signal 86. The resulting data modulated signal is passed to the intensity modulator 88 for remodulation with the clock frequency 90 to generate a dual or otherwise multimodulated optical information signal 92. Because the intensity modulation based on the clock is a non-random, completely periodic pattern, little or no cross talk due to XGM is generated by the DRAs 44 so long as there is a slight velocity mismatch in the forward pumping direction. FIGURE 5 illustrates the waveform of the dual modulated optical information signal 92.

FIGURE 6 illustrates details of the optical receiver 32 in accordance with one embodiment of the present invention. In this embodiment, the optical receiver 32 receives a demultiplexed optical information signal 24 with the data modulated on the phase of the carrier signal with phase shift keying. It will be understood that the optical receiver 32 may be otherwise suitably configured to receive and detect data otherwise encoded in an optical information signal 24 without departing from the scope of the present invention.

Referring to FIGURE 6, the optical receiver 32 includes an asymmetric interferometer 100 and a detector 102. The interferometer 100 is an asymmetric Mach-Zender or other suitable interferometer operable to convert a non-intensity modulated optical information signal 24 into an intensity modulated optical information signal for detection of data by the detector 102. Preferably, the Mach-Zender interferometer 100 with wavelength dependent loss and good rejection characteristics for the channel spacing.

The Mach-Zender interferometer 100 splits the received optical signal into two interferometer paths 110

and 112 of different lengths and then combines the two paths 110 and 112 interferometrically to generate two complimentary output signals 114 and 116. In particular, the optical path difference (L) is equal to the symbol rate (B) multiplied by the speed of light (c) and divided by the optical index of the paths (n). Expressed mathematically:  $L=Bc/n$ .

In a particular embodiment, the two path lengths 110 and 112 are sized based on the symbol, or bit rate to provide a one symbol period, or bit shift. In this embodiment, the Mach-Zender interferometer 100 has a wavelength dependent loss that increases the rejection of neighboring channels when channel spacing comprises the symbol transmission rate multiple within 0.4 to 0.6 of an integer as previously described.

The detector 102 is a dual or other suitable detector. In one embodiment, the dual detector 102 includes photodiodes 120 and 122 connected in series in a balanced configuration and a limiting amplifier 124. In this embodiment, the two complimentary optical outputs 114 and 116 from the Mach-Zender interferometer 100 are applied to the photodiodes 120 and 122 for conversion of the optical signal to an electrical signal. The limiting electronic amplifier 124 converts the electrical signal to a digital signal (0 or 1) depending on the optical intensity delivered by the interferometer 100. In another embodiment, the detector 102 is a single detector with one photodiode 122 coupled to output 116. In this embodiment, output 114 is not utilized.

FIGURE 7 illustrates the frequency response of the asymmetric Mach-Zender interferometer 100 in accordance with one embodiment of the present invention. In this embodiment, channel spacing comprises the symbol



transmission rate multiple within 0.4 to 0.6 of an integer as previously described. As can be seen, optical frequency of neighboring channels is automatically rejected by the asymmetric Mach-Zender interferometer 100 to aid channel rejection of the demultiplexer 30. It will be understood that the asymmetric Mach-Zender interferometer may be used in connection with other suitable channel spacings.

FIGURES 8A-C illustrate details of the demultiplexer 30 in accordance with one embodiment of the present invention. In this embodiment, phase or frequency modulated optical information signals 24 are converted to intensity modulate optical information signals within the demultiplexer 30 of the WDM receiver 14 and/or before demultiplexing or between demultiplexing steps. It will be understood that the demultiplexer 30 may otherwise suitably demultiplex and/or separate the optical information signals 24 from the WDM signal 26 without departing from the scope of the present invention.

Referring to FIGURE 8A, the demultiplexer 30 comprises a plurality of demultiplex elements 130 and a multi-channel format converter 131. Each demultiplex element 130 separates a received set of channels 132 into two discrete sets of channels 134. Final channel separation is performed by dielectric filters 136 which each filter a specific channel wavelength 138.

The multichannel format converter 131 converts phase modulation to intensity modulation and may be an asymmetric Mach-Zender interferometer with a one-bit shift to convert non-intensity modulated signals to intensity modulated signals as previously described in connection with interferometer 100 or suitable optical device having a periodical optical frequency response

that converts at least two phase or frequency modulated channels into intensity modulated WDM signal channels. The intensity-conversion interferometer may be prior to the first stage demultiplex element 130, between the  
5 first and second stages or between other suitable stages. The other demultiplex elements 130 may comprise filters or non-conversion Mach-Zender interferometers operable to filter the incoming set of channels 132 into the two sets of output channels 134.

10 In a particular embodiment, the multichannel format converter 131 is an asymmetric Mach-Zender interferometer with a free spectral range coinciding with the WDM channel spacing or its integer sub-multiple. This allows  
15 all the WDM channels to be converted within the Mach-Zender interferometer simultaneously. In this embodiment, a channel spacing may be configured based on the channel bit rate which defines the free spectral range. Placement of the intensity-conversion Mach-Zender interferometer in the demultiplexer 30 eliminates the  
20 need for the interferometer 100 at each optical receiver 32 which can be bulky and expensive. In addition, the demultiplexer 30 including the Mach-Zender and other demultiplexer elements 130 may be fabricated on a same chip which reduces the size and cost of the WDM receiver  
25 14.

Referring to FIGURE 8B, the demultiplexer 30 comprises a plurality of wavelength interleavers 133 and a multichannel format converter 135 for each set of  
30 interleaved optical information signals output by the last stage wavelength interleavers 133. Each wavelength interleaver 133 separates a received set of channels into two discrete sets of interleaved channels. The multichannel format converters 135 may be asymmetric

Mach-Zender interferometers with a one-bit shift to convert non-intensity modulated signals to intensity modulated signals as previously described in connection with interferometer 100 or other suitable optical device.

5 Use of the wavelength interleavers as part of the WDM demultiplexing in front of the format converters allow several WDM channels to be converted simultaneously in one Mach-Zender interferometer even if the free spectral range of the interferometer does not coincide with an integer multiple of the WDM channel spacing. FIGURE 8C illustrates transmissions of four Mach-Zender interferometers for a particular embodiment of the demultiplexer 30 using wavelength interleavers 133 in which the free spectral range is three quarters of the channel spacing. In this embodiment, the four Mach-Zender interferometers may be used to convert all of the WDM channels.

FIGURE 9 illustrates a method for transmitting information in an optical communication system using distributed amplification in accordance with one embodiment of the present invention. In this embodiment, data signals are phase-shift keyed onto the carrier signal and the signal is amplified during transmission using discrete and distributed amplification.

20 Referring to FIGURE 9, the method begins at step 140 in which the phase of each disparate wavelength optical carrier signal is modulated with a data signal 74 to generate the optical information signals 24. At step 142, the optical information signals 24 are multiplexed into the WDM signal 26. At step 143, the WDM signal 26 is transmitted in the optical link 16.

Proceeding to step 144, the WDM signal 26 is amplified along the optical link 16 utilizing discrete

and distributed amplification. As previously described, the WDM signal 26 may be amplified at discrete points using EDFAs 42 and distributedly amplified using bi-directional DRAs 44. Because the data signals are modulated onto the phase of the carrier signal, cross talk between channels from XGM due to forward pumping amplification is eliminated. Accordingly, the signal-to-noise ratio can be maximized and the signals may be transmitted over longer distances without regeneration.

10 Next, at step 145, the WDM signal 26 is received by the WDM receiver 14. At step 146, the WDM signal 26 is demultiplexed by the demultiplexer 30 to separate out the optical information signals 24. At step 147, the phase modulated optical information signals 24 are converted to  
15 intensity modulated signals for recovery of the data signal 74 at step 148. In this way, data signals 74 are transmitted over long distances using forward or bi-directional pumping distributed amplification with a low bit-to-noise ratio.

20 FIGURE 10 illustrates a bi-directional optical communication system 150 in accordance with one embodiment of the present invention. In this embodiment, the bi-directional communication system 150 includes WDM transmitters 152 and WDM receivers 154 at each end of an  
25 optical link 156. The WDM transmitters 152 comprise optical senders and a multiplexer as previously described in connection with the WDM transmitter 12. Similarly, the WDM receivers 154 comprise demultiplexers and optical receivers as previously described in connection with the  
30 WDM receiver 14.

At each end point, the WDM transmitter and receiver set is connected to the optical link 156 by a routing device 158. The routing device 158 may be an optical

circulator, optical filter, or optical interleaver filter capable of allowing egress traffic to pass onto the link 156 from WDM transmitter 152 and to route ingress traffic from the link 156 to WDM receiver 154.

5       The optical link 156 comprises bi-directional discrete amplifiers 160 and bi-directional distributed amplifiers 162 spaced periodically along the link. The bi-directional discrete amplifiers 160 may comprise EDFA amplifiers as previously described in connection with  
10       amplifiers 42. Similarly, the distributed amplifiers 162 may comprise DRA amplifiers including co-pumping and counter-pumping lasers 164 and 166 as previously described in connection with DRA amplifiers 44.

15       In operation, a WDM signal is generated and transmitted from each end point to the other end point and a WDM signal is received from the other end point. Along the length of the optical link 156, the WDM signals are amplified using bi-directional-pumped DRA 162. Because data is not carried in the form of optical  
20       intensity, cross talk due to XGM is eliminated. Thus, DRA and other suitable distributed amplification may be used in long-haul and other suitable bi-directional optical transmission systems.

25       FIGURE 11 illustrates an optical sender 200 and an optical receiver 202 in accordance with another embodiment of the present invention. In this embodiment, the optical sender 200 and the optical receiver 204 communicate to fine-tune modulation for improved transmission performance of the optical information  
30       signals 24. It will be understood that modulation of the optical information signals 24 may be otherwise fine-tuned using downstream feedback without departing from the scope of the present invention.

Referring to FIGURE 11, the optical sender 200 comprises a laser 210, a modulator 212, and a data signal 214 which operate as previously described in connection with the laser 70, the modulator 72 and the data signal 74. A controller 216 receives bit error rate or other indication of transmission errors from the downstream optical receiver 202 and adjust the modulation depth of modulator 212 based on the indication to reduce and/or minimize transmission errors. The controller 216 may adjust the amplitude, intensity, phase, frequency and/or other suitable modulation depth of modulator 212 and may use any suitable control loop or other algorithm that adjusts modulation alone or in connection with other characteristics toward a minimized or reduced transmission error rate. Thus, for example, the controller 216 may adjust a non-intensity modulation depth and a depth of the periodic intensity modulation in the optical sender 80 to generate and optimize multimodulated signals.

The optical receiver 202 comprises an interferometer 220 and a detector 222 which operate as previously described in connection with interferometer 100 and detector 102. A forward error correction (FEC) decoder 224 uses header, redundant, symptom or other suitable bits in the header or other section of a SONET or other frame or other transmission protocol data to determine bit errors. The FEC decoder 224 corrects for detected bit errors and forwards the bit error rate or other indicator of transmission errors to a controller 226 for the optical receiver 202.

The controller 226 communicates the bit error rate or other indicator to the controller 216 in the optical sender 200 over an optical supervisory channel (OSC) 230.

The controllers 216 and 226 may communicate with each other to fine-tune modulation depth during initiation or setup of the transmission system, periodically during operation of the transmission system, continuously during operation of the transmission system or in response to predefined trigger events. In this way, modulation depth is adjusted based on received signal quality measured at the receiver to minimize chromatic dispersion, non-linear effects, receiver characteristics and other unpredictable and/or predictable characteristics of the system.

FIGURE 12 illustrates details of the modulator 212 in accordance with one embodiment of the present invention. In this embodiment, the modulator 212 employs phase and intensity modulation to generate a bi-modulated optical information signal. The phase and intensity modulation depth is adjusted based on receiver-side feedback to minimize transmission errors.

Referring to FIGURE 12, the modulator 212 includes for phase modulation such as phase shift keying a bias circuit 230 coupled to an electrical driver 232. The bias circuit 230 may be a power supply and the electrical driver 232 a broadband amplifier. The bias circuit 230 is controlled by the controller 216 to output a bias signal to the electrical driver 232. The bias signal provides an index for phase modulation. The electrical driver 232 amplifies the data signal 214 based on the bias signal and outputs the resulting signal to phase modulator 234. Phase modulator 234 modulates the receive bias-adjusted data signal onto the phase of the carrier signal output by the laser 210 to generate a phase modulated optical information signal 236.

For intensity modulation such as intensity shift keying, the modulator 212 includes a bias circuit 240

coupled to an electrical driver 242. The bias circuit 240 is controlled by the controller 216 to output a bias signal to the electrical driver 242. The bias signal acts as an intensity modulation index. The electrical driver 242 amplifies a network, system or other suitable clock signal 244 based on the bias signal and outputs the resulting signal to the intensity modulator 246. The intensity modulator 246 is coupled to the phase modulator 234 and modulates the receive bias-adjusted clock signal onto the phase modulated optical information signal 236 to generate the bi-modulated optical information signal for transmission to a receiver. It will be understood that phase and intensity modulation at the transmitter may be otherwise suitably controlled based on receiver-side feedback to minimize transmission errors of data over the optical link.

FIGURE 13 illustrates a method for fine tuning modulation depth of an optical information signal using receiver side information in accordance with one embodiment of the present invention. The method begins at step 250 in which an optical carrier is modulated with a data signal 214 at the optical sender 200. Next, at step 252, the resulting optical information signal 24 is transmitted to the optical receiver 202 in a WDM signal 26.

Proceeding to step 254, the data signal 214 is recovered at the optical receiver 204. At step 256, the FEC decoder 224 determines a bit error rate for the data based on bits in the SONET overhead. At step 258, the bit error rate is reported by the controller 226 of the optical receiver 202 to the controller 216 of the optical sender 200 over the OSC 230.



Next, at decisional step 260, the controller 216 determines whether modulation is optimized. In one embodiment, modulation is optimized when the bit error rate is minimized. If the modulation is not optimized, the No branch of decisional step 260 leads to step 262 in which the modulation depth is adjusted. Step 262 returns to step 250 in which the data signal 214 is modulated with the new modulation depth and transmitted to the optical receiver 202. After the modulation depth is optimized from repetitive trials and measurements or other suitable mechanisms, the Yes branch of decisional step 260 leads to the end of the process. In this way, transmission performance is improved and transmission errors minimized.

FIGURE 14 illustrates an optical communication system 275 distributing a clock signal in an information channel in accordance with one embodiment of the present invention. In this embodiment, pure clock is transmitted in channels to one, more or all nodes in the optical system 275.

Referring to FIGURE 14, optical system 275 includes a WDM transmitter 280 coupled to a WDM receiver 282 over an optical link 284. The WDM transmitter 280 includes a plurality of optical senders 290 and a WDM multiplexer 292. Each optical sender 290 generates an optical information signal 294 on one of a set of discrete wavelengths at the channel spacing. In the clock channel 296, the optical sender 290 generates an optical information signal 294 with at least one characteristic modulated to encode the clock signal. In the data channels 297, the optical sender 290 generates an optical information signal 294 with at least one characteristic modulated to encode a corresponding data signal.

The optical signals 294 from the clock and data channels 296 and 297 are multiplexed into a signal WDM signal 298 by the WDM multiplexer 292 for transmission on the optical link 284. Along the optical link 284, the  
5 signal may be amplified by discrete and/or distributed amplifiers as previously described.

The WDM receiver 282 receives, separates and decodes the optical information signals 294 to recover the included data and clock signals. In one embodiment, the  
10 WDM receiver 282 includes a WDM demultiplexer 310 and a plurality of optical receivers 312. The WDM demultiplexer 310 demultiplexes the optical information signals 294 from the single WDM signal 298 and sends each optical information signal 294 to a corresponding optical  
15 receiver 312.

Each optical receiver 312 optically or electrically recovers the encoded data or clock signal from the corresponding signal 294. In the clock channel 296, the clock signal is recovered and forwarded to the optical  
20 receivers 312 in the data channels 297 for use in data extraction and forward error correction. The transmission of pure clock in an information channel allows a more stable clock recovery with less jitter. The stable clock may be used by forward error correction  
25 to improve the bit error rate even in the presence of jitter and poor optical signal quality.

FIGURE 15 illustrates an optical receiver 320 for extracting a clock signal from a multimodulated signal in accordance with one embodiment of the present invention.  
30 In this embodiment, the optical receiver 320 receives a demultiplexed optical information signal with data phase modulated onto a carrier signal that is then remodulated with intensity modulation synchronized with the network,

system or other suitable clock as described in connection with the optical sender 80. The optical receiver 320 extracts the clock information from the optical signal and uses the stable clock to recover data from the phase modulated signal of the channel. Thus, each channel can recover its own clock.

Referring to FIGURE 15, the optical receiver 320 includes an interferometer 322 and a detector 324 as previously described in connection with the optical receiver 32. The interferometer 322 receives the multimodulated signal and converts the phase modulation into intensity modulation for recovery of the data signal 330 by the detector 324.

A clock recovery element 326 comprises a photodiode and/or other suitable components to recover the clock signal before phase-to-intensity conversion of the data signal. The clock recovery element 326 may comprise a phase lock loop, a tank circuit, a high quality filter and the like. The clock recovery element 326 receives the multimodulated signal and recovers the clock signal 332 from the intensity modulation.

The data signal 330 and the recovered clock signal 332 are output to a digital flip flop or other suitable data recovery circuit 334. In this way, the optical receiver 320 extracts the clock information from the optical signal before the phase-to-intensity conversion of the data signal and provides a stable clock recovery with less jitter even with poor optical signal quality corresponding to a bit error rate in the range of  $1e^{-2}$ .

Although the present invention has been described with several embodiments, various changes and modifications may be suggested to one skilled in the art. It is intended that the present invention encompass such

changes and modifications as fall within the scope of the  
appended claims.

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60  
61  
62  
63  
64  
65  
66  
67  
68  
69  
70  
71  
72  
73  
74  
75  
76  
77  
78  
79  
80  
81  
82  
83  
84  
85  
86  
87  
88  
89  
90  
91  
92  
93  
94  
95  
96  
97  
98  
99  
100  
101  
102  
103  
104  
105  
106  
107  
108  
109  
110  
111  
112  
113  
114  
115  
116  
117  
118  
119  
120  
121  
122  
123  
124  
125  
126  
127  
128  
129  
130  
131  
132  
133  
134  
135  
136  
137  
138  
139  
140  
141  
142  
143  
144  
145  
146  
147  
148  
149  
150  
151  
152  
153  
154  
155  
156  
157  
158  
159  
160  
161  
162  
163  
164  
165  
166  
167  
168  
169  
170  
171  
172  
173  
174  
175  
176  
177  
178  
179  
180  
181  
182  
183  
184  
185  
186  
187  
188  
189  
190  
191  
192  
193  
194  
195  
196  
197  
198  
199  
200  
201  
202  
203  
204  
205  
206  
207  
208  
209  
210  
211  
212  
213  
214  
215  
216  
217  
218  
219  
220  
221  
222  
223  
224  
225  
226  
227  
228  
229  
230  
231  
232  
233  
234  
235  
236  
237  
238  
239  
240  
241  
242  
243  
244  
245  
246  
247  
248  
249  
250  
251  
252  
253  
254  
255  
256  
257  
258  
259  
260  
261  
262  
263  
264  
265  
266  
267  
268  
269  
270  
271  
272  
273  
274  
275  
276  
277  
278  
279  
280  
281  
282  
283  
284  
285  
286  
287  
288  
289  
290  
291  
292  
293  
294  
295  
296  
297  
298  
299  
300  
301  
302  
303  
304  
305  
306  
307  
308  
309  
310  
311  
312  
313  
314  
315  
316  
317  
318  
319  
320  
321  
322  
323  
324  
325  
326  
327  
328  
329  
330  
331  
332  
333  
334  
335  
336  
337  
338  
339  
340  
341  
342  
343  
344  
345  
346  
347  
348  
349  
350  
351  
352  
353  
354  
355  
356  
357  
358  
359  
360  
361  
362  
363  
364  
365  
366  
367  
368  
369  
370  
371  
372  
373  
374  
375  
376  
377  
378  
379  
380  
381  
382  
383  
384  
385  
386  
387  
388  
389  
390  
391  
392  
393  
394  
395  
396  
397  
398  
399  
400  
401  
402  
403  
404  
405  
406  
407  
408  
409  
410  
411  
412  
413  
414  
415  
416  
417  
418  
419  
420  
421  
422  
423  
424  
425  
426  
427  
428  
429  
430  
431  
432  
433  
434  
435  
436  
437  
438  
439  
440  
441  
442  
443  
444  
445  
446  
447  
448  
449  
450  
451  
452  
453  
454  
455  
456  
457  
458  
459  
460  
461  
462  
463  
464  
465  
466  
467  
468  
469  
470  
471  
472  
473  
474  
475  
476  
477  
478  
479  
480  
481  
482  
483  
484  
485  
486  
487  
488  
489  
490  
491  
492  
493  
494  
495  
496  
497  
498  
499  
500  
501  
502  
503  
504  
505  
506  
507  
508  
509  
510  
511  
512  
513  
514  
515  
516  
517  
518  
519  
520  
521  
522  
523  
524  
525  
526  
527  
528  
529  
530  
531  
532  
533  
534  
535  
536  
537  
538  
539  
540  
541  
542  
543  
544  
545  
546  
547  
548  
549  
550  
551  
552  
553  
554  
555  
556  
557  
558  
559  
560  
561  
562  
563  
564  
565  
566  
567  
568  
569  
570  
571  
572  
573  
574  
575  
576  
577  
578  
579  
580  
581  
582  
583  
584  
585  
586  
587  
588  
589  
590  
591  
592  
593  
594  
595  
596  
597  
598  
599  
600  
601  
602  
603  
604  
605  
606  
607  
608  
609  
610  
611  
612  
613  
614  
615  
616  
617  
618  
619  
620  
621  
622  
623  
624  
625  
626  
627  
628  
629  
630  
631  
632  
633  
634  
635  
636  
637  
638  
639  
640  
641  
642  
643  
644  
645  
646  
647  
648  
649  
650  
651  
652  
653  
654  
655  
656  
657  
658  
659  
660  
661  
662  
663  
664  
665  
666  
667  
668  
669  
670  
671  
672  
673  
674  
675  
676  
677  
678  
679  
680  
681  
682  
683  
684  
685  
686  
687  
688  
689  
690  
691  
692  
693  
694  
695  
696  
697  
698  
699  
700  
701  
702  
703  
704  
705  
706  
707  
708  
709  
710  
711  
712  
713  
714  
715  
716  
717  
718  
719  
720  
721  
722  
723  
724  
725  
726  
727  
728  
729  
730  
731  
732  
733  
734  
735  
736  
737  
738  
739  
740  
741  
742  
743  
744  
745  
746  
747  
748  
749  
750  
751  
752  
753  
754  
755  
756  
757  
758  
759  
760  
761  
762  
763  
764  
765  
766  
767  
768  
769  
770  
771  
772  
773  
774  
775  
776  
777  
778  
779  
780  
781  
782  
783  
784  
785  
786  
787  
788  
789  
790  
791  
792  
793  
794  
795  
796  
797  
798  
799  
800  
801  
802  
803  
804  
805  
806  
807  
808  
809  
810  
811  
812  
813  
814  
815  
816  
817  
818  
819  
820  
821  
822  
823  
824  
825  
826  
827  
828  
829  
830  
831  
832  
833  
834  
835  
836  
837  
838  
839  
840  
841  
842  
843  
844  
845  
846  
847  
848  
849  
850  
851  
852  
853  
854  
855  
856  
857  
858  
859  
860  
861  
862  
863  
864  
865  
866  
867  
868  
869  
870  
871  
872  
873  
874  
875  
876  
877  
878  
879  
880  
881  
882  
883  
884  
885  
886  
887  
888  
889  
890  
891  
892  
893  
894  
895  
896  
897  
898  
899  
900  
901  
902  
903  
904  
905  
906  
907  
908  
909  
910  
911  
912  
913  
914  
915  
916  
917  
918  
919  
920  
921  
922  
923  
924  
925  
926  
927  
928  
929  
930  
931  
932  
933  
934  
935  
936  
937  
938  
939  
940  
941  
942  
943  
944  
945  
946  
947  
948  
949  
950  
951  
952  
953  
954  
955  
956  
957  
958  
959  
960  
961  
962  
963  
964  
965  
966  
967  
968  
969  
970  
971  
972  
973  
974  
975  
976  
977  
978  
979  
980  
981  
982  
983  
984  
985  
986  
987  
988  
989  
990  
991  
992  
993  
994  
995  
996  
997  
998  
999  
1000  
1001  
1002  
1003  
1004  
1005  
1006  
1007  
1008  
1009  
1010  
1011  
1012  
1013  
1014  
1015  
1016  
1017  
1018  
1019  
1020  
1021  
1022  
1023  
1024  
1025  
1026  
1027  
1028  
1029  
1030  
1031  
1032  
1033  
1034  
1035  
1036  
1037  
1038  
1039  
1040  
1041  
1042  
1043  
1044  
1045  
1046  
1047  
1048  
1049  
1050  
1051  
1052  
1053  
1054  
1055  
1056  
1057  
1058  
1059  
1060  
1061  
1062  
1063  
1064  
1065  
1066  
1067  
1068  
1069  
1070  
1071  
1072  
1073  
1074  
1075  
1076  
1077  
1078  
1079  
1080  
1081  
1082  
1083  
1084  
1085  
1086  
1087  
1088  
1089  
1090  
1091  
1092  
1093  
1094  
1095  
1096  
1097  
1098  
1099  
1100  
1101  
1102  
1103  
1104  
1105  
1106  
1107  
1108  
1109  
1110  
1111  
1112  
1113  
1114  
1115  
1116  
1117  
1118  
1119  
1120  
1121  
1122  
1123  
1124  
1125  
1126  
1127  
1128  
1129  
1130  
1131  
1132  
1133  
1134  
1135  
1136  
1137  
1138  
1139  
1140  
1141  
1142  
1143  
1144  
1145  
1146  
1147  
1148  
1149  
1150  
1151  
1152  
1153  
1154  
1155  
1156  
1157  
1158  
1159  
1160  
1161  
1162  
1163  
1164  
1165  
1166  
1167  
1168  
1169  
1170  
1171  
1172  
1173  
1174  
1175  
1176  
1177  
1178  
1179  
1180  
1181  
1182  
1183  
1184  
1185  
1186  
1187  
1188  
1189  
1190  
1191  
1192  
1193  
1194  
1195  
1196  
1197  
1198  
1199  
1200  
1201  
1202  
1203  
1204  
1205  
1206  
1207  
1208  
1209  
1210  
1211  
1212  
1213  
1214  
1215  
1216  
1217  
1218  
1219  
1220  
1221  
1222  
1223  
1224  
1225  
1226  
1227  
1228  
1229  
1230  
1231  
1232  
1233  
1234  
1235  
1236  
1237  
1238  
1239  
1240  
1241  
1242  
1243  
1244  
1245  
1246  
1247  
1248  
1249  
1250  
1251  
1252  
1253  
1254  
1255  
1256  
1257  
1258  
1259  
1260  
1261  
1262  
1263  
1264  
1265  
1266  
1267  
1268  
1269  
1270  
1271  
1272  
1273  
1274  
1275  
1276  
1277  
1278  
1279  
1280  
1281  
1282  
1283  
1284  
1285  
1286  
1287  
1288  
1289  
1290  
1291  
1292  
1293  
1294  
1295  
1296  
1297  
1298  
1299  
1300  
1301  
1302  
1303  
1304  
1305  
1306  
1307  
1308  
1309  
1310  
1311  
1312  
1313  
1314  
1315  
1316  
1317  
1318  
1319  
1320  
1321  
1322  
1323  
1324  
1325  
1326  
1327  
1328  
1329  
1330  
1331  
1332  
1333  
1334  
1335  
1336  
1337  
1338  
1339  
1340  
1341  
1342  
1343  
1344  
1345  
1346  
1347  
1348  
1349  
1350  
1351  
1352  
1353  
1354  
1355  
1356  
1357  
1358  
1359  
1360  
1361  
1362  
1363  
1364  
1365  
1366  
1367  
1368  
1369  
1370  
1371  
1372  
1373  
1374  
1375  
1376  
1377  
1378  
1379  
1380  
1381  
1382  
1383  
1384  
1385  
1386  
1387  
1388  
1389  
1390  
1391  
1392  
1393  
1394  
1395  
1396  
1397  
1398  
1399  
1400  
1401  
1402  
1403  
1404  
1405  
1406  
1407  
1408  
1409  
1410  
1411  
1412  
1413  
1414  
1415  
1416  
1417  
1418  
1419  
1420  
1421  
1422  
1423  
1424  
1425  
1426  
1427  
1428  
1429  
1430  
1431  
1432  
1433  
1434  
1435  
1436  
1437  
1438  
1439  
1440  
1441  
1442  
1443  
1444  
1445  
1446  
1447  
1448  
1449  
1450  
1451  
1452  
1453  
1454  
1455  
1456  
1457  
1458  
1459  
1460  
1461  
1462  
1463  
1464  
1465  
1466  
1467  
1468  
1469  
1470  
1471  
1472  
1473  
1474  
1475  
1476  
1477  
1478  
1479  
1480  
1481  
1482  
1483  
1484  
1485  
1486  
1487  
1488  
1489  
1490  
1491  
1492  
1493  
1494  
1495  
1496  
1497  
1498  
1499  
1500  
1501  
1502  
1503  
1504  
1505  
1506  
1507  
1508  
1509  
1510  
1511  
1512  
1513  
1514  
1515  
1516  
1517  
1518  
1519  
1520  
1521  
1522  
1523  
1524  
1525  
1526  
1527  
1528  
1529  
1530  
1531  
1532  
1533  
1534  
1535  
1536  
1537  
1538  
1539  
1540  
1541  
1542  
1543  
1544  
1545  
1546  
1547  
1548  
1549  
1550  
1551  
1552  
1553  
1554  
1555  
1556  
1557  
1558  
1559  
1560  
1561  
1562  
1563  
1564  
1565  
1566  
1567  
1568  
1569  
1570  
1571  
1572  
1573  
1574  
1575  
1576  
1577  
1578  
1579  
1580  
1581  
1582  
1583  
1584  
1585  
1586  
1587  
1588  
1589  
1590  
1591  
1592  
1593  
1594  
1595  
1596  
1597  
1598  
1599  
1600  
1601  
1602  
1603  
1604  
1605  
1606  
1607  
1608  
1609  
1610  
1611  
1612  
1613  
1614  
1615  
1616  
1617  
1618  
1619  
1620  
1621  
1622  
1623  
1624  
1625  
1626  
1627  
1628  
1629  
1630  
1631  
1632  
1633  
1634  
1635  
1636  
1637  
1638  
1639  
1640  
1641  
1642  
1643  
1644  
1645  
1646  
1647  
1648  
1649  
1650  
1651  
1652  
1653  
1654  
1655  
1656  
1657  
1658  
1659  
1660  
1661  
1662  
1663  
1664  
1665  
1666  
1667  
1668  
1669  
1670  
1671  
1672  
1673  
1674  
1675  
1676  
1677  
1678  
1679  
1680  
1681  
1682  
1683  
1684  
1685  
1686  
1687  
1688  
1689  
1690  
1691  
1692  
1693  
1694  
1695  
1696  
1697  
1698  
1699  
1700  
1701  
1702  
1703  
1704  
1705  
1706  
1707  
1708  
1709  
1710  
1711  
1712  
1713  
1714  
1715  
1716  
1717  
1718  
1719  
1720  
1721  
1722  
1723  
1724  
1725  
1726  
1727  
1728  
1729  
1730  
1731  
1732  
1733  
1734  
1735  
1736  
1737  
1738  
1739  
1740  
1741  
1742  
1743  
1744  
1745  
1746  
1747  
1748  
1749  
1750  
1751  
1752  
1753  
1754  
1755  
1756  
1757  
1758  
1759  
1760  
1761  
1762  
1763  
1764  
1765  
1766  
1767  
1768  
1769  
1770  
1771  
1772  
1773  
1774  
1775  
1776  
1777  
1778  
1779  
1780  
1781  
1782  
1783  
1784  
1785  
1786  
1787  
1788  
1789  
1790  
1791  
1792  
1793  
1794  
1795  
1796  
1797  
1798  
1799  
1800  
1801  
1802  
1803  
1804  
1805  
1806  
1807  
1808  
1809  
1810  
1811  
1812  
1813  
1814  
1815  
1816  
1817  
1818  
1819  
1820  
1821  
1822  
1823  
1824  
1825  
1826  
1827  
1828  
1829  
1830  
1831  
1832  
1833  
1834  
1835  
1836  
1837  
1838  
1839  
1840  
1841  
1842  
1843  
1844  
1845  
1846  
1847  
1848  
1849  
1850  
1851  
1852  
1853  
1854  
1855  
1856  
1857  
1858  
1859  
1860  
1861  
1862  
1863  
1864  
1865  
1866  
1867  
1868  
1869  
1870  
1871  
1872  
1873  
1874  
1875  
1876  
1877  
1878  
1879  
1880  
1881  
1882  
1883  
1884  
1885  
1886  
1887  
1888  
1889  
1890  
1891  
1892  
1893  
1894  
1895  
1896  
1897  
1898  
1899  
1900  
1901  
1902  
1903  
1904  
1905  
1906  
1907  
1908  
1909  
1910  
1911  
1912  
1913  
1914  
1915  
1916  
1917  
1918  
1919  
1920  
1921  
1922  
1923  
1924  
1925  
1926  
1927  
1928  
1929  
1930  
1931  
1932  
1933  
1934  
1935  
1936  
1937  
1938  
1939  
1940  
1941  
1942  
1943  
1944  
1945  
1946  
1947  
1948  
1949  
1950  
1951  
1952  
1953  
1954  
1955  
1956  
1957  
1958  
1959  
1960  
1961  
1962  
1963  
1964  
1965  
1966  
1967  
1968  
1969  
1970  
1971  
1972  
1973  
1974  
1975  
1976  
1977  
1978  
1979  
1980  
1981  
1982  
1983  
1984  
1985  
1986  
1987  
1988  
1989  
1990  
1991  
1992  
1993  
1994  
1995  
1996  
1997  
1998  
1999  
2000  
2001  
2002  
2003  
2004  
2005  
2006  
2007  
2008  
2009  
2010  
2011  
2012  
2013  
2014  
2015  
2016  
2017  
2018  
2019  
2020  
2021  
2022  
2023  
2024  
2025  
2026  
2027  
2028  
2029  
2030  
2031  
2032  
2033  
2034  
2035  
2036  
2037  
2038  
2039  
2040  
2041  
2042  
2043  
2044  
2045  
2046  
2047  
2048  
2049  
2050  
2051  
2052  
2053  
2054  
2055  
2056  
2057  
2058  
2059  
2060  
2061  
2062  
2063  
2064  
2065  
2066  
2067  
2068  
2069  
2070  
2071  
2072  
2073  
2074  
2075  
2076  
2077  
2078  
2079  
2080  
2081  
2082  
2083  
2084  
2085  
2086  
2087  
2088  
2089  
2090  
2091  
2092  
2093  
2094  
2095  
2096  
2097  
2098  
2099  
2100  
2101  
2102  
2103  
2104  
2105  
2106  
2107  
2108  
2109  
2110  
2111  
2112  
2113  
2114  
2115  
2116  
2117  
2118  
2119  
2120  
2121  
2122  
2123  
2124  
2125  
2126  
2127  
2128  
2129  
2130  
2131  
2132  
2133  
2134  
2135  
2136  
2137  
2138  
2139  
2140  
2141  
2142  
2143  
2144  
2145  
2146  
2147  
2148  
2149  
2150  
2151  
2152  
2153  
2154  
2155  
2156  
2157  
2158  
2159  
2160  
2161  
2162  
2163  
2164  
2165  
2166  
2167  
2168  
2169  
2170  
2171  
2172  
2173  
2174  
2175  
2176  
2177  
2178  
2179  
2180  
2181  
2182  
2183  
2184  
2185  
2186  
2187  
2188  
2189  
2190  
2191  
2192  
2193  
2194  
2195  
2196  
2197  
2198  
2199  
2200  
2201  
2202  
2203  
2204  
2205  
2206  
2207  
2208  
2209  
2210  
2211  
2212  
2213  
2214  
2215  
2216